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Application of investigation techniques to identify an arson fire

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ABSTRACT
Determining the cause of an arson fire is the most difficult part of fire investigation. In this study, the researcher used various clues and several pieces of fire debris collected from the actual fire site to conduct a series of experiments and analyses in sequence, starting from metallographic analysis to inductively coupled plasma optical emission spectrometry and then a thermal analysis experiment to determine the cause of a fire. It was found that when the temperature was elevated at a rate of 2 °C/min, polyurethane (PU) foam, a structural component of refrigerators, started thermal decomposition. At about 130 °C, the thermal decomposition accelerated, and eventually at 384 °C, about 4883.33 J/g of maximum heat was released. In the end, remaining debris was about 4.96%. Therefore, the combustion of PU foam is an ultrafast type of combustion reaction. The content as well as the experimental procedure of the study is useful for fire investigators in determining the cause of arson fires.

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KEYWORDS
Fire investigation; arson fire; metallographic analysis; thermal analysis experiment; inductively coupled plasma optical emission spectrometry (ICP-OES); PU foam

1. Introduction

The most important task in fire investigation is to identify causes for the break out of fire, because its results can not only be used to improve a building's fire safety strategies, but also better determine the allocation of responsibility among people who are or may be responsible for a fire, or as an important legal document in criminal law cases (Shen, Huang, and Chien 2008). Among fires, arson fire can be regarded as criminal behavior involving deliberate damage to property or buildings. Such criminal processes may be easy to implement, but the investigation is very difficult after fires have broken out (Pert, Baron, and Birkett 2006). In the past, in the UK, 2100 arson incidents occurred within one week, which resulted in two people dead and 55 people injured along with a £40 million loss (Sugg 2003). In the light of such tragic results, it is impossible to ignore the extent of the danger of arson attacks.

The cause of the fire examined in this study was hard to determine, and in fact, was very likely to have been arson. The incident happened on 12 June 2012 at a factory in Dayuan Township of Taoyuan County, Taiwan. At that time of the day, there was no one in the factory. The factory owner had tripled the fire insurance amount three months earlier, owing to the severe flooding in the vicinity of the factory, caused by torrential rain. When the fire broke out, a large quantity of raw materials, semi-finished, and finished pharmaceutical products were stored in the warehouse in the back of the factory. According to fire investigation findings, the most damaged area of this factory was the aforementioned warehouse with an area of about 100 m^2. Other areas in the factory suffered only minor smoke and heat damage. However, losses from this fire were reported to be up to around US$1 million. Because of the above-mentioned unusual factors, the official fire investigation unit collected several samples from possible ignition positions and conducted gas chromatography–mass spectrometry (GC–MS) tests in accordance with the analytic method for ignitable liquid residues described in references (Lentini 2006; Locke, Basara, and Sandercock 2009). The test results showed no obvious ignitable liquid residues. Consequently, by referring to the guidelines of fire scene reconstruction of NFPA921 (NFPA 2008), this study applied other analytic tests to conduct every task in this actual fire investigation, as shown in Figure 1, and compared and analyzed each test result to confirm the reason for the fire. The results of this study may be used as a reference for other cases of arson investigation in the future.

2. Fire scene observation

The fire was discovered and reported by the next-door neighbor. The firefighters arrived at this fire site within 10 min after receiving the report. They only took about 22 min to extinguish the fire and the recorded time period of this fire was about 32 min. Weather conditions when the fire broke out included rain and a northwest wind at a speed of 1.5 m/s. Upon arrival, the firemen found smoke pouring from the door of the factory warehouse and the refrigerator located on the east side of the warehouse was burning. There was no special odor or explosions at the spot. Owing to the requirement to implement site disaster relief, the firemen broke the metal external wall near a 170-cm-wide window in the east side of the warehouse and sprinkled water into the factory to carry out the rescue operation. After site

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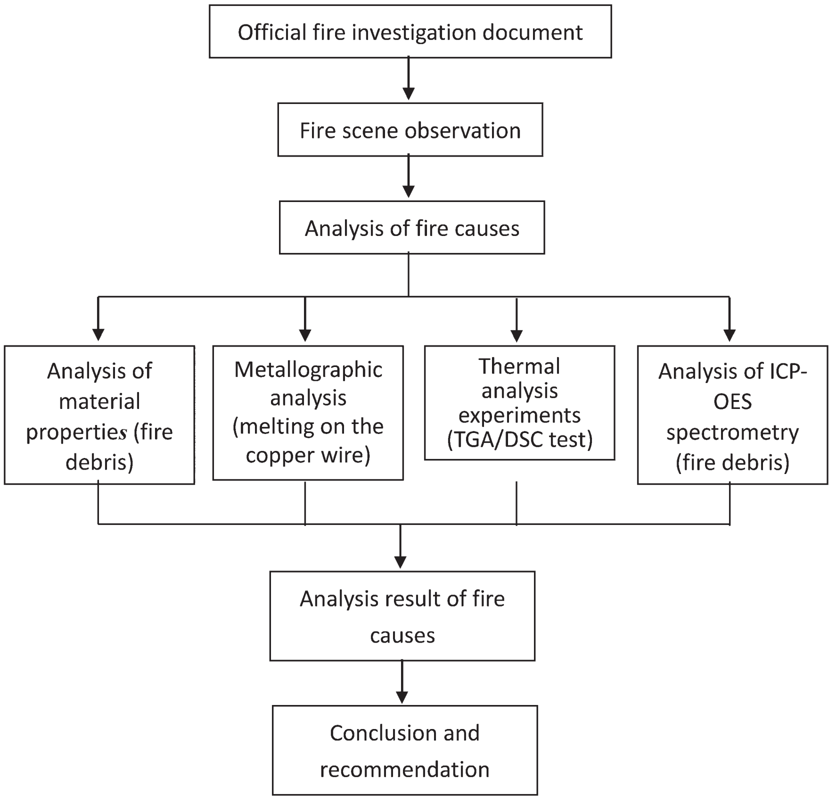
Official fire investigation document
Fire scene observation
Analysis of fire causes
Analysis of material properties (fire debris)
Metallographic analysis (melting on the copper wire)
Thermal analysis experiments (TGA/DSC test)
Analysis of ICP-OES spectrometry (fire debris)
Analysis result of fire causes
Conclusion and recommendation

Figure 1. Flow chart of task in this actual fire investigation operations.

investigation, the most likely ignition position was suspected to be, as described by the first firefighters to arrive, a place near the refrigerator behind the fan in the eastern side of the warehouse, as shown in Figure 2.

3. The analysis of fire causes

3.1. Analysis of material properties

According to interviews with the staff member who left the factory last, he left the factory at about 4:00 pm the day before the fire broke out after he turned off the power and set the security system. At that time, there should have been nobody inside the factory. When the fire broke out, substances stored in the warehouse refrigerator included powdered enzymes, balsam pears, cabbage, carrot, and turmeric which are all incombustible agricultural products, and some finished and semi-finished products in aluminum foil capsules and cartons which cannot burn without an external fire source. In addition, according to this staff member, smoking is usually prohibited within the factory. As there was no residue of ignition sources such as cigarette butts found at the fire site, smoking is therefore excluded as the cause of fire.

3.2. Metallographic analysis

The research staff went to inspect the site of the fire incident and found several electrical wires at the back of an electric fan, as shown in Figure 2. One of the electric wires showed melting, while others had only the insulation burned with no significant sign of melting. To assess if the fire was triggered by an electrical short circuit, the researcher conducted a metallographic analysis on the melted part of that specific wire. First, a sample was obtained from the melted part. The sample was put into the extraction fluid and then solidified. Afterward, a twin variable-speed grinder-polisher was used for grinding and polishing before the researcher observed the microstructure of the sample through an optical microscope (600×), as shown in Figure 3. It can be seen from the microstructure shown in Figure 3 that the air pockets inside the microstructure were quite consistent in terms of size and shape (round). Their diameters were between 0.1 and 0.3 mm, and there were many air pockets (a high %). In contrast, the references (Chi 2012; Yu 2007) have shown that the melted part of a powered electrical wire triggering a fire because of a short circuit is more likely to have long column-shaped, rather than round-shaped, air pockets in the metallographic microstructure. Moreover, the percentage of air pockets should be low, about 0.4%. In other words, what this study observed, as shown in Figure 3, was quite different from the characteristics described by other researchers (Chi 2012; Yu 2007). Therefore, one can conclude that the melting on the sample was secondary melting; that is, it was indirectly produced by the spreading of a high-temperature fire from elsewhere. According to information provided by factory employees and fire fighters, there was no other electrical device at the speculated starting location of the fire, and moreover, when the incident happened, the general power supply of the factory was off. All things considered, the fire was not caused by an electrical short circuit.

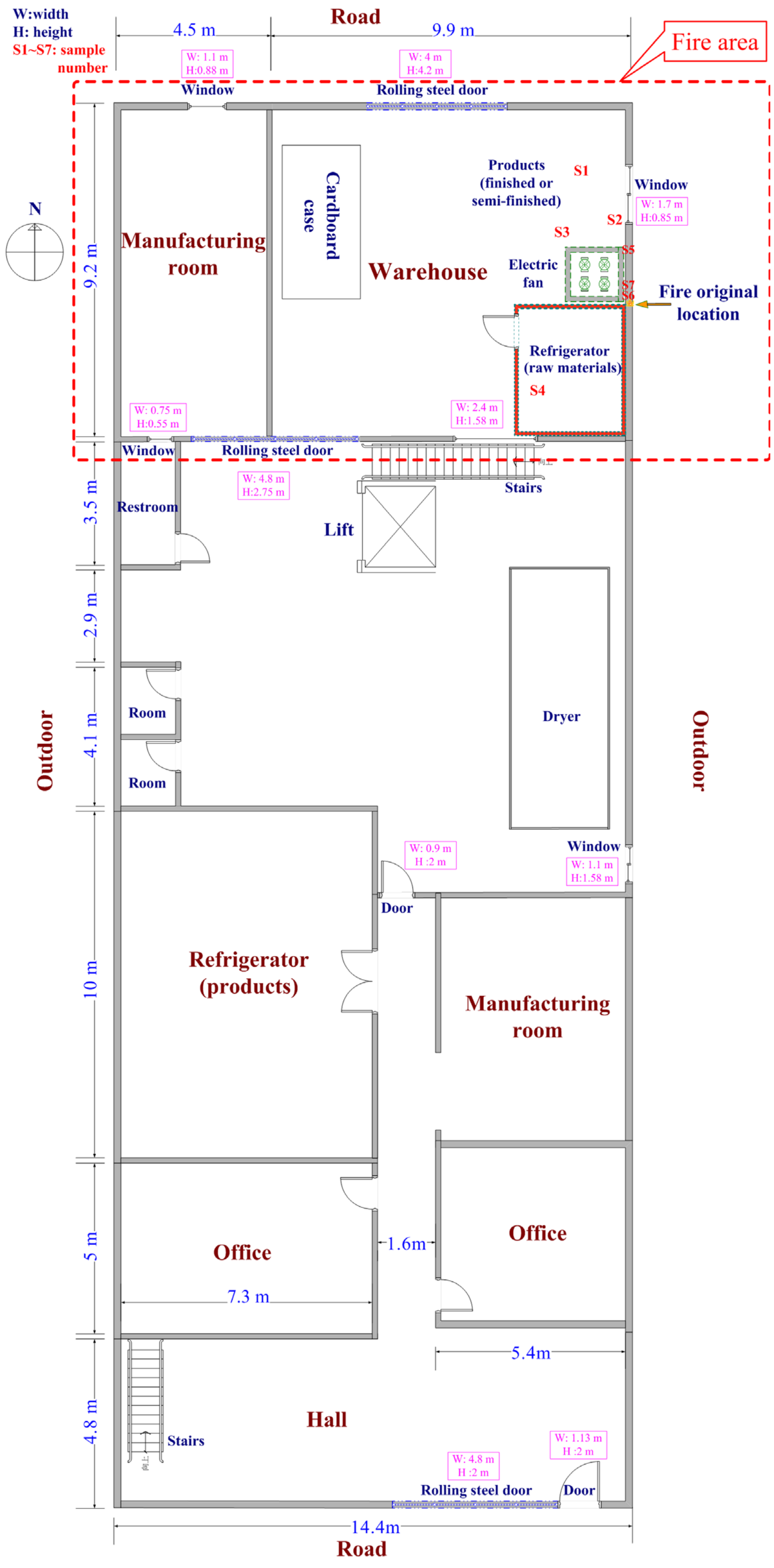

Figure 2. Layout of the fire area behind the factory.

3.3. Test of ICP-OES

As the official fire investigation units had carried out the GC–MS test for ignitable liquid residues, this study conducted a sample composition analysis through inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer, OPTIMA 5100DV), or ICP-OES for short, referred to in the reference (Chiang et al. 2007). First, 5 ml of diesel oil were used to carry out an ICP-OES test. As the test results for the main components Fe (45.08), Ca (30.56), Cr (7.046), and Zn (6.436) shown in order of abundance in Table 1 are similar to the test results of

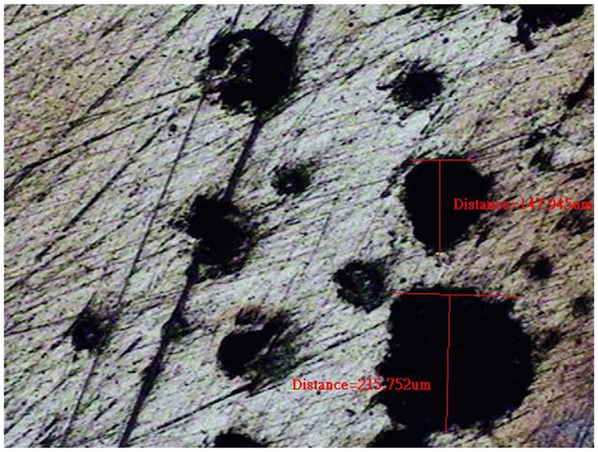

Figure 3. Microstructure image of the melting by metallographic analysis test (600×).

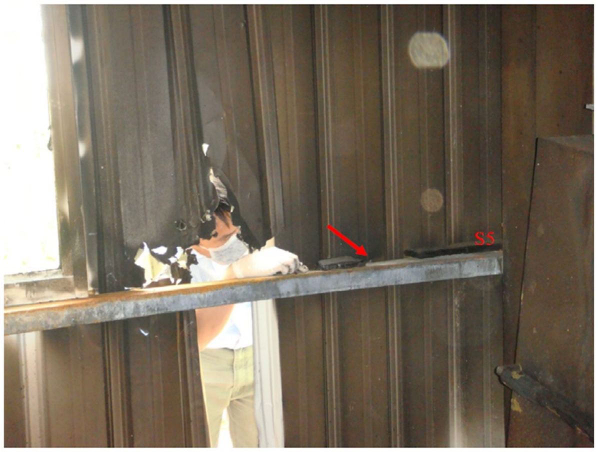

Figure 4. Photos of the wooden stick (red arrow signal) near the ignition position and locations of sample S5.

Chiang et al. (2007), this sample was used as the control sample with which to compare the test results of other samples.

Damages caused by the fire are largely located at the east side of the warehouse, including the goods' area, refrigerator, and the area behind the fan. After carefully reviewing the fire debris from these areas, the research team took three samples, S1, S2, and S3, from the goods' area, and two samples, S5 and S6, from the type C steel rod behind the fan with one sample, S7, forwarded by the official forensic unit. From inside the refrigerator, only one sample, S4, was obtained due to the limited amount of debris onsite and the fact that the clean panel of the freezer is badly damaged from the fire with only two remaining side panels. Figure 2 shows the locations of samples S1–S7. After obtaining samples S1–S7, the research team dried the samples in the laboratory at 60 °C for 4 h. The samples were then placed in the solution consisting of 25% nitric acid and 75% hydrochloric acid, and heated to a boil. Once the solution cooled, it was filtered and extracted for the ICP test. The contents of samples S1–S7 are shown in Table 1.

The high concentrations of Al (436.4) and Ca (356.1) in the S1 sample shown in Table 1 is understandable because a large quantity of finished products, such as aluminum foil, capsules, and cartons, were stored at the sampling location. However, the analysis showed that the change trend of ingredients' concentrations in this sample is not consistent with the results of the aforementioned diesel control sample. Except for the higher concentration of Ca (154.5) in the S2 sample, the concentration of the rest of the ingredients of S2 and S3 samples shown in Table 1 are inconsistent with the change trend of the control sample. Table 1 also shows that the analysis results of the S4 sample, collected from the inside of the refrigerator for agricultural material storage, are also inconsistent with those of the diesel control sample. Near the ignition source and the 170-cm-wide window, the research team had found a long piece of wood above the C-type steel rod, as indicated with a red arrow in Figure 4. As both the front and end sides of the wood had been seriously carbonized, residue of the wood near the window side were collected as sample S5, the wood from the opposite side near the ignition source as sample S6 and a sample of this piece of debris from the official investigation is sample S7 shown in Table 1. Additionally, Figure 5 shows that the test results for samples S6 and S7 as well as the diesel sample taken near the ignition point differ greatly in Si, Ca, Fe, Zn, and Mg. In the ICP test results, which show the presence and concentration of 13 constituents, the curves do not match. Therefore, it can be concluded that samples S6 and S7 taken near the fire starting point do not contain diesel.

The analysis results of the above-mentioned samples investigated by the official fire investigation unit and this research team revealed that no residues show burning of an ignitable liquid human caused flammable liquid ignition, therefore, can be excluded as a cause of fire.

3.4. *Thermal analysis experiments (Thermogravimetric Analysis (TGA)/Differential Scanning Calorimetery (DSC) test)*

Near the speculated fire's original location, the research staff found the most seriously burned item, the refrigerator (Figure 2). The main structure of the refrigerator was the clean

Table 1. Test results of the ICP-OEP spectrometer by each sample.

NO	Ba	Si	Al	Ca	Cr	Mn	Fe	Ni	Cu	Zn	Pb	Mg	Ti
Diesel oil	0.152	1.660	1.340	30.56	7.046	0.549	45.08	0.187	0.151	6.426	0.079	3.516	0.067
S1	7.262	12.07	436.4	356.1	0.194	0.761	22.93	0.090	0.848	2.382	0.121	32.85	11.11
S2	0.480	8.101	18.10	154.5	0.171	0.90	14.04	0.160	0.440	11.77	0.094	20.90	0.327
S3	0.090	2.447	3.397	7.915	0.015	0.026	1.132	0.010	0.049	0.175	0.014	1.230	0.054
S4	0.125	1.485	0.544	14.33	0.011	0.102	0.459	0.010	0.083	0.236	0.015	11.97	0.011
S5	0.192	0.855	0.926	11.18	0.065	0.188	4.757	0.032	0.058	4.363	0.041	3.017	0.068
S6	0.277	0.509	0.523	11.19	0.046	0.052	0.969	0.014	0.011	2.490	0.012	0.570	0.550
S7	0.3	11.7	12.5	61.5	0.02	0.1	10	0.01	0.01	0.3	0.02	9.1	0.52

Note: unit: mg/L.

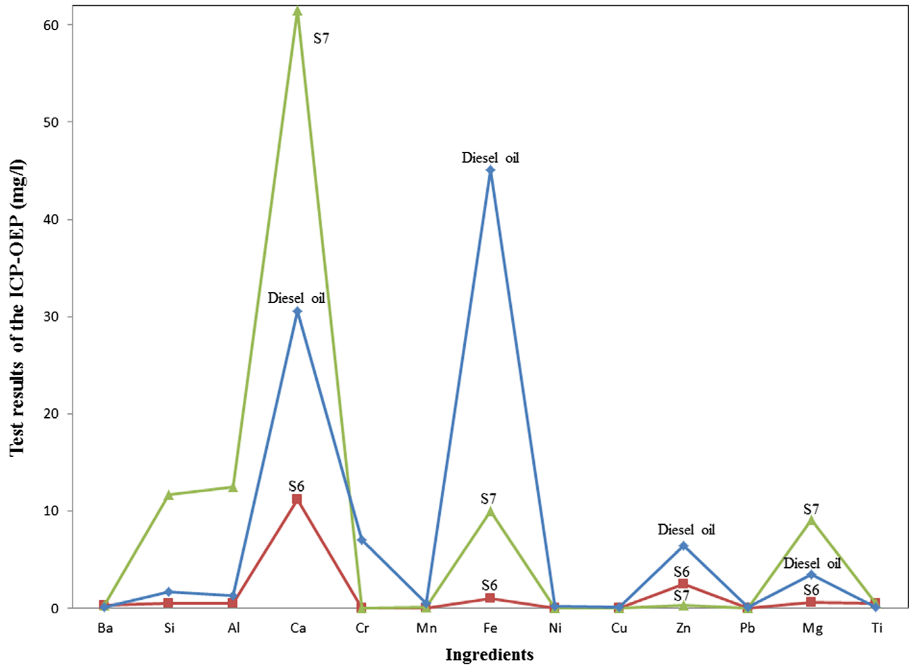

Figure 5. Distributed curve of the ICP-OEP spectrometer's test results by S6, S7, and diesel oil samples.

panels, and the 50-mm-thick polyurethane (PU) foam inside the clean panels found at the fire scene was completely burned, only the 1.2-mm-thick stainless steel boards originally at the two sides of the PU foam remained. To explore the combustion of these clean panels in the fire incident, the research staff obtained a sample from an intact clean panel (neither burned nor damaged) found in the factory to perform the TGA/DSC test (Mettler Toledo STARe system TGA/DSC1-SF) with the PU foam inside the sampled clean panel. The PU foam sample was about 14.0593 mg, and at a heating rate of 2 °C/min, the thermal reaction of the sample from 30 to 400 °C was recorded, as shown in Figure 6(a). The weight loss of the PU foam sample in the TGA/DSC test is shown in Figure 6(b), and the result suggests that when the sample was heated to 40 °C, thermal decomposition began, and at 130 °C, the process of thermal decomposition accelerated (the slope of the curve in the graph increased). Therefore, when the temperature of the fire exceeds 130 °C, the PU foam inside the panel is likely to start to burn because of the heat. It is also shown in Figure 6(a) that when heating up the PU foam sample to 384 °C, a lot of thermal energy was released, and the maximum heat released was about 4883.33 J/g (the highest point of the curve in the graph). It can be found in Figure 6(b) that when the sample was heated to 384 °C, the weight dropped quickly (reflected by the rapid decline of the slope of the curve), and when the temperature reached 400 °C, the exothermic reaction of the sample due to combustion was finished. Only about 4.96% debris was left. Therefore, this type of combustion reaction is a type of ultrafast combustion reaction. When examining the thermal reaction data of the PU foam, it was found that the figures were much higher than those of many flammable liquids, which have also caused several serious fire incidents or explosions in the past. When PU foam is ignited and starts to burn, it will release a large amount of heat, which will cause the fire to grow and to spread, resulting in serious fire disasters. PU foam inside refrigerator panels is definitely a highly inflammable material.

3.5. *Analysis results*

According to security system records, there was an abnormal movement reaction in the 170-cm window behind the east side of the factory warehouse. However, because of the severe water accumulation in a nearby area, security personnel could not immediately reach the field to investigate. In addition, after careful examination of the residues of sample S6 (the samples closest to the ignition position), the appearances of some residues after burning are very similar to the debris from cartons in the product area. Judging from relevant site locations, the possibility of the debris of burned cartons in the finished product area naturally drifting to the location of sample S6 is very low.

After discussing the above results, the research team and official fire investigators suspected that someone had opened that window and ignited the cartons of product piled up next to the window, and then pushed the burning cartons to the ignition position, as shown in Figure 2, with a long piece of wood, as shown in Figure 4. As the temperature of this flame is generally higher than the temperature required to decompose the PU foam described in the aforementioned Section, when this flame was pushed to the ignition position, it quickly ignited the PU foam on the side of the refrigerator and led the fire to spread out quickly, resulting in the fire incident. Therefore, based on fire cause analysis, arson is suspected to be the most likely cause.

4. Conclusions

Despite the rapid development of arson investigation techniques recently, the extent of the difficulties involved in arson investigation has not changed. For example, in this case,

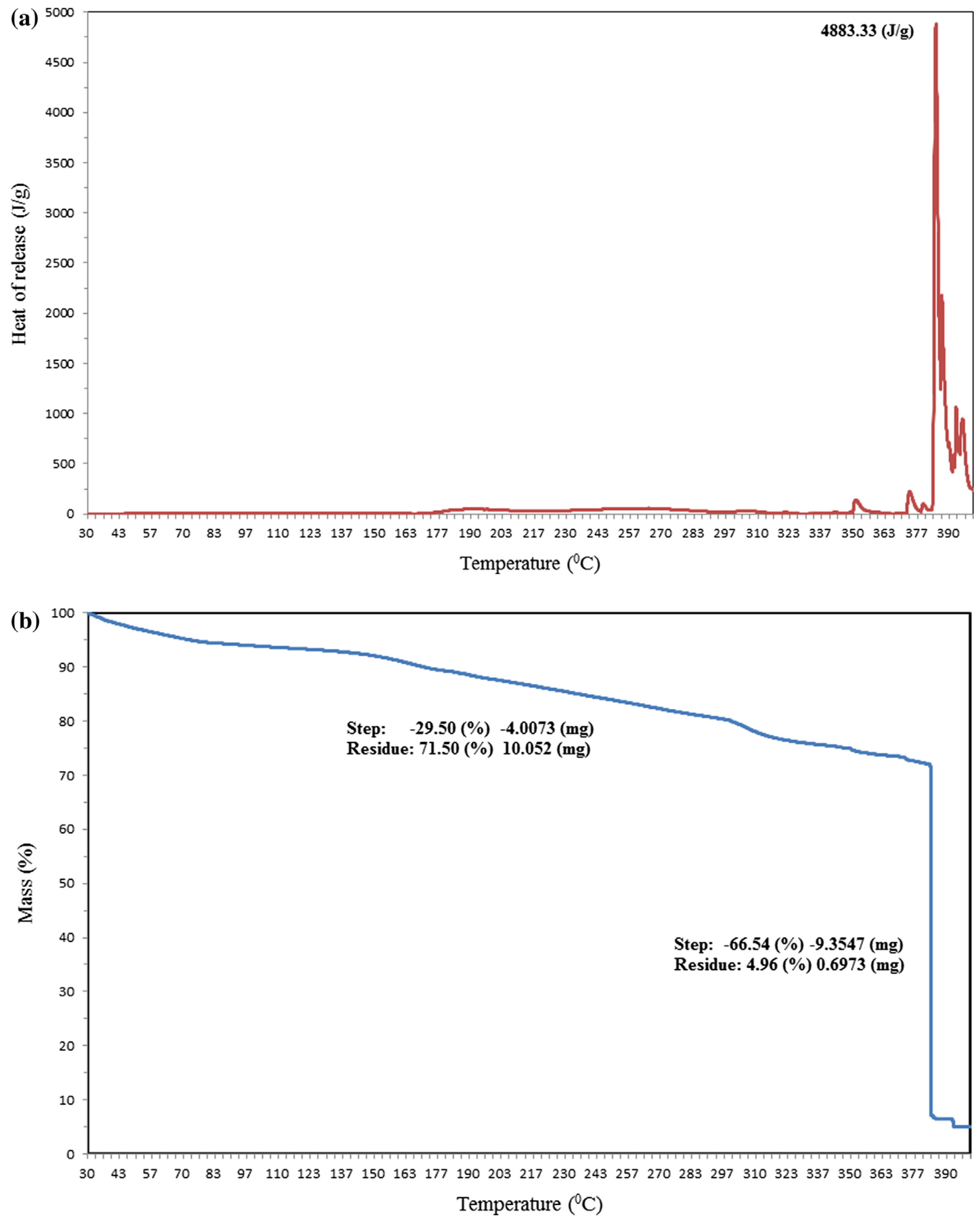

Figure 6. Combustion test of PU foam by TGA/DSC (a) per gram of heat release; (b) loss of weight.

the fire damaged area in this study is only 50 m^2, in order to determine the real fire cause, in addition to collecting samples on site to conduct relevant tests, it is also necessary to use considerable human resources to collect possible clues such as records of personnel interviews, electrical equipment use, security systems and environmental occurrences. In particular, the residue samples from the fire are quite different from normal chemical materials. The complexity of internal components in residue samples is difficult to imagine. In this study, before carrying out the ICP-OES test, the sample had been mixed with strong acid and heated to boiling so as to remove organic compounds in the sample by nitration. The sampling locations of S1, S2, and S3 were relatively close, but figures of partial composition of these three samples shown in Table 1 are quite different. It can be seen that the ingredient analysis of fire debris on the spot not only has to consider the types of original substances, but also the mixture of other unrelated material due to the fire fighting process, fire site cleanup by the investigating officers as well as environmental and climatic factors. If combined with the deliberate arrangement of arson and criminal behaviors, the interpretation of experimental data will become more difficult.

Furthermore, the official investigation unit found a suspected ignitable liquid residue near the fire position (sample S6) and dug out the concrete block under that position to perform a GC–MS test, but failed to find any evidence of ignitable liquid residue. Therefore, the official unit transferred the aforementioned concrete block to our team to conduct an ICP-OES test. As shown in Table 1, the analysis results of sample S7 display inconsistency with the composition of the diesel oil sample. Therefore, it can be understood that the above two test methods will not only conflict with each other, but also have the effect of reconfirmation. Thus, if there is any doubt about GC–MS test results in a fire investigation, they can be re-verified by applying the ICP-OES test directly to the used samples and comparing the results with those of GC–MS.

As most arson attacks are carefully planned and arranged, if the area burnt by a fire is very large, it will be much more difficult for the investigating officers to find the relevant evidence. Besides, if there is any delay to action being taken, the available fire residues at the site might be destroyed or contaminated. During an arson investigation, a highly challenging task, fire investigators have to be familiar with the principles and operations of various test techniques, and more importantly, they have to integrate clues and information from witnesses, police, fire fighters, and security and insurance personnel to gradually minimize the scope of investigation. By rebuilding the fire scene this way, a just and objective fire investigation can be ensured.

Nomenclature

J/g	heat release
°C	temperature
%	low of weigh
L	liter

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